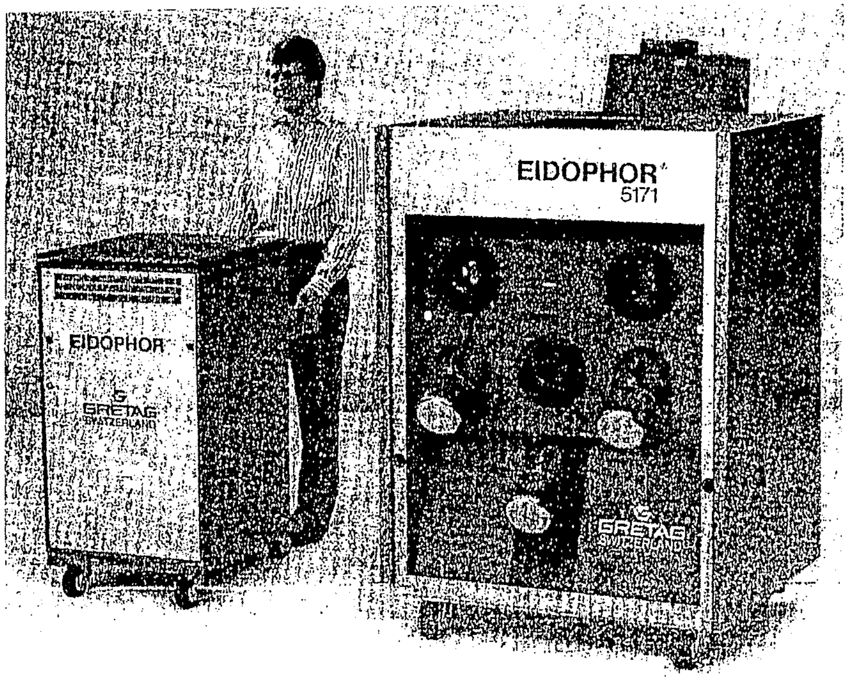

Figure 6.28 Gretag Eidophor oil-film light valve projection display. (Photo courtesy of SAIC, McLean, Va.)

are used in military and aerospace applications for dome and helmet-mounted simulators and command and control centers. Non-aerospace applications include large coliseum and stadium displays.

6.4 LIQUID-CRYSTAL LIGHT VALVE PROJECTION DISPLAYS

Liquid-crystal light valve (LCLV) projection display technology has been growing extremely rapidly in recent years, building upon the results of research activity in liquid crystals and liquid-crystal displays. In this type of display, liquid-crystal light valves are used to modulate white light from the light source into an image, which is then projected onto the screen. The LCLVs can be used in either

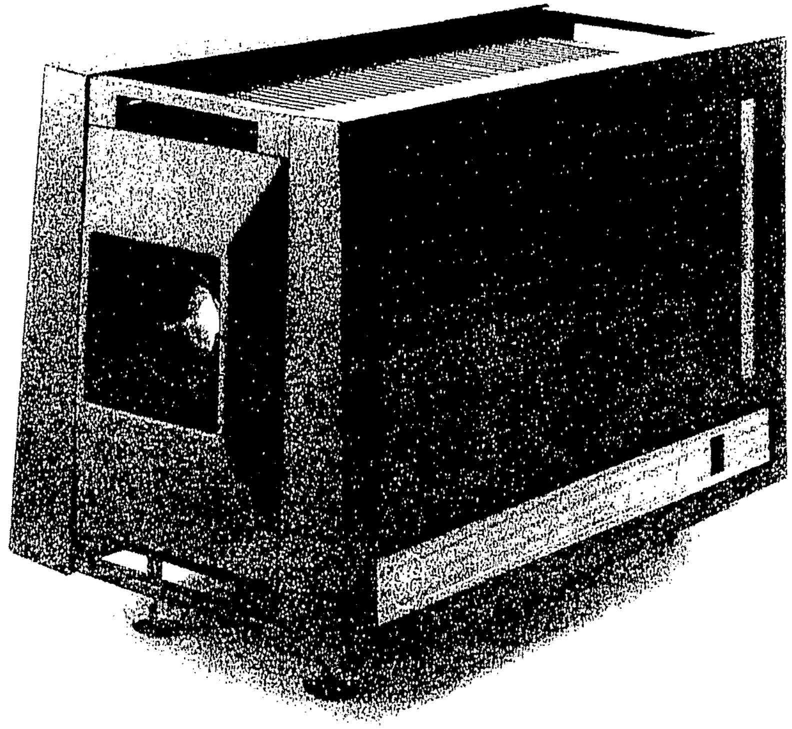

Figure 6.29 General Electric Talaria MP oil-film light valve projection display. (Photo courtesy of General Electric, Syracuse, N.Y.)

a transmissive or reflective configuration. These are illustrated in Figures 6.30 and 6.31. Reflective LCLV projection displays usually use a polarizing beam splitter to reflect light toward the light valve on the first pass, then transmit the modulated image to the projection optics on the return path.

The biggest advantage of LCLV image projection displays is the separation of light generation from image generation, allowing the two to vary independently.

A disadvantage of many LCLV projection displays is that only light of a single polarization can be used by the LCLV, resulting in an immediate loss of half the system light. This disadvantage can be eliminated, however, by using recent developments in techniques to repolarize light of the wrong polarization and render

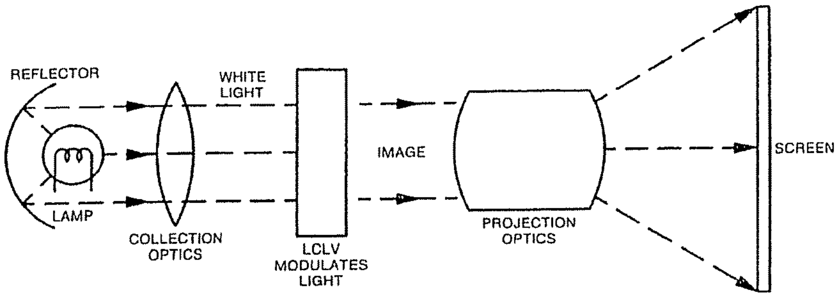

Figure 6.30 Transmissive LCLV projection display components.

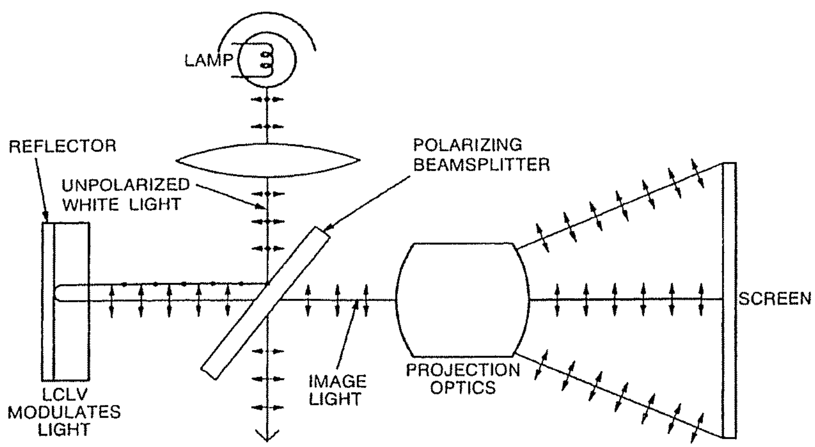

Figure 6.31 Reflective LCLV projection display components.

it usable, or by using new liquid-crystal types that do not operate on the polarization of the light.

There are a variety of ways in which light valves can be addressed. These include optical addressing, which can be done with a laser or a CRT—for example, thermal addressing, which is accomplished with an IR laser—or, more recently, active-matrix addressing. The active-matrix-addressed LCLV uses a

matrix of active elements, such as thin-film transistors (TFTs), to provide individual addressing of each pixel.

6.4.1 Active-Matrix-Addressed LCLV Projection Displays

The results of intense research and development that has occurred recently in the area of active-matrix-addressed LC direct-view displays have been used in the area of projection displays. In 1986 Seiko-Epson introduced the first full-color projection display using active-matrix-addressed LCLVs (Morozumi et al., 1986). Other systems quickly followed. Active-matrix LCLV (AMLCLV) projectors have added another class of projection displays: small, portable, and inexpensive consumer and low-end industrial systems.

Operating Principles of AMLCLV Projection Displays

An active-matrix light valve used in a projection display is very similar to the ones used for direct-view active-matrix liquid-crystal flat-panel displays. Active elements are used to provide individual light transmission control of each pixel. In projection display applications the diffuse backlight used for direct-view flat panels is replaced with a pseudocollimated light source. Light passing through the light valve is modulated with image information, which is projected onto the diffuse screen, where the image is formed. This type of system is illustrated in Figure 6.32.

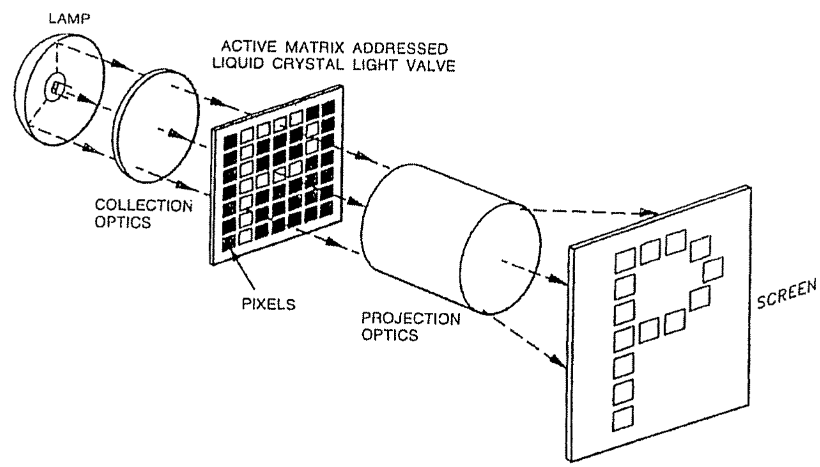

Figure 6.32 AMLCLV projection display components.

The majority of LC projection displays being developed use a twisted nematic liquid-crystal configuration similar to direct-view LCDs. The light valve blocks or transmits light by operating on its polarization state. Since the light valve uses only one of the polarization states, 50% of the light is lost. This is being remedied with techniques for converting light of the "wrong" polarization so that it is usable, minimizing polarization losses (Toide and Kugo, 1991; Schadt and Funfschilling, 1990).

A new type of AMLV being developed for projection displays uses polymer-dispersed liquid crystals (PDLC). In a PDLC light valve, small liquid-crystal spheres are suspended in a polymer matrix. The liquid crystal is designed such that in one orientation its index of refraction matches that of the polymer and the light valve is clear. In the other state the refractive indices do not match, and light is scattered by the light valve (Doane et al., 1988; Fergason, 1985). Therefore, in one state—the on state—the LCLV transmits all light through to the projection lens; and in the off state, light is scattered and does not make it to the projection lens. Several systems of this type are under development (Jones et al., 1991; Hirai et al., 1991; Takizawa et al., 1991).

One difference between a direct-view and a projection AMLCLV display is that the projection display uses three different light valves—one each for red, green, and blue—as opposed to the direct-view technique of using color filters over the pixels to provide the different colors. This eliminates the color filter layer of the liquid-crystal cell and provides a resolution and light throughput advantage over using one light valve to provide all three colors.

White-light sources typically used are tungsten halogen, metal halide, and xenon. Dichroic mirrors are used to divide the light into its component colors. The red, green, and blue light then passes through the respective light valves, which are coded with video information. The three color images can then be combined, again with dichroic coatings, and projected onto the screen or combined at the screen as in the off-axis CRT system. The layout of the Seiko-Epson display is shown in Figure 6.33. This system is pictured in Figure 6.34.

The beam-combining and beam-splitting operations in the active-matrix LCLV display are more efficient in terms of light throughput than in a CRT system. As discussed in Section 6.2, dichroic coatings operate most efficiently with polarized, collimated, single-wavelength light. The light transmitted through an LV system is not of a single wavelength, but it is usually polarized and semicollimated. This greatly simplifies the design of the beam-combining system. For this reason, most active-matrix LCLV projection systems use an on-axis optical system, which does not add greatly to the size or cost of the system as it does in the CRT projection display.

Characteristics of AMLCLV Projection Displays

The color gamut of an active-matrix LCLV projection display is determined by the spectral characteristics of the dichroic coatings used on the beam splitters and

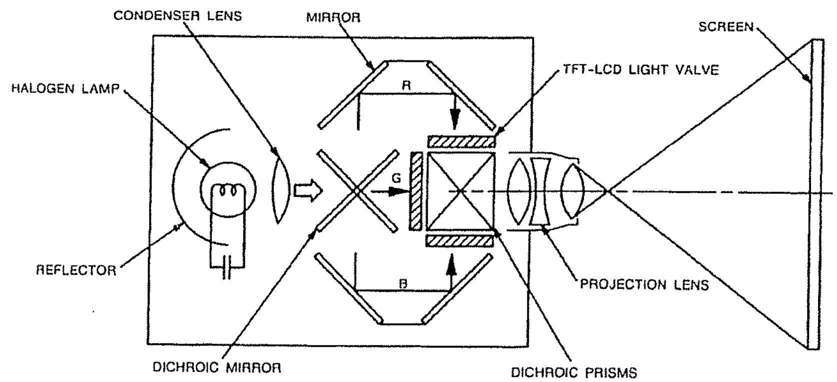

Figure 6.33 Seiko-Epson full-color AMLCLV projection display layout (Courtesy Morozumi et al. 1986)

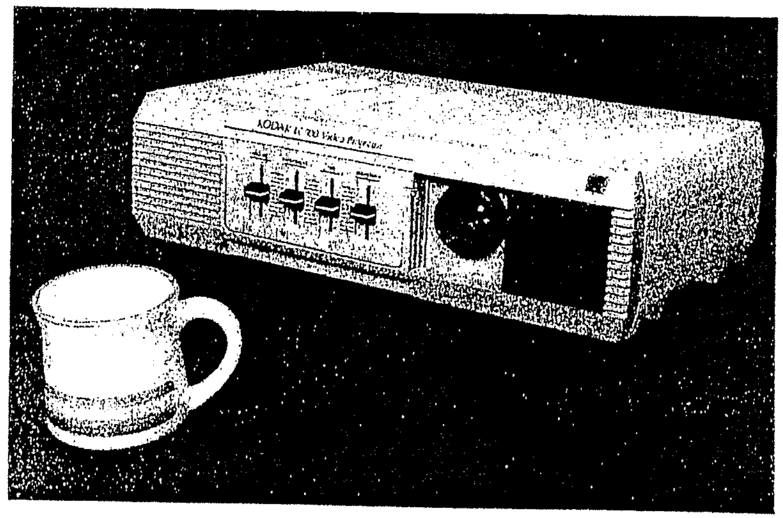

Figure 6.34 Picture of Seiko-Epson AMLCLV projection display. (The light valves are made by Seiko-Epson, but the system was originally marketed by Kodak.)

combiners. Figure 6.35 gives an example of the color gamut of the Seiko-Epson system (Morozumi et al., 1986).

The resolution of a particular AMLCLV projection display depends on the number of pixels contained in the light valve. In order to increase the resolution of the display, either the pixel density or the size of the light valve must be increased. Several systems are commercially available, including the Seiko-Epson unit with a pixel resolution of 320 × 220 and a Sharp display with a resolution of 382 × 234. Many more systems have been reported (Sakamoto et al. 1991; Takeuchi et al., 1991; Fukuta et al., 1991; Kobayashi et al., 1989; Kunigata et al., 1990; Noda et al., 1989; Timmers et al., 1989) with resolutions available up to 1422 × 960 pixels (Takubo et al., 1989). These resolution numbers refer to the number of pixels in the light valve, which is usually the resolution-limiting element in an active-matrix LCLV projection display. These resolution values do not directly compare with values reported for other systems such as CRT or OFLV projectors (Barten, 1991; Stroomer, 1989).

The image luminance provided by a liquid-crystal light valve projector is based on the lumens out of the lamp and the efficiency of the optical system and light valve, given by the equation

$$B_S = W_{\text{lamp}}\eta_{\text{lamp}}\Omega T_{\text{lv}}T_{\text{optics}}G/A \qquad (6.4)$$

where W_{lamp} is the lamp power in watts, η_{lamp} is the lamp efficacy in lumens per watt, Ω is the collection efficiency of the collection optics, T_{lv} is the transmission of the light valve, and T_{optics} is the projection optical system transmission. Major

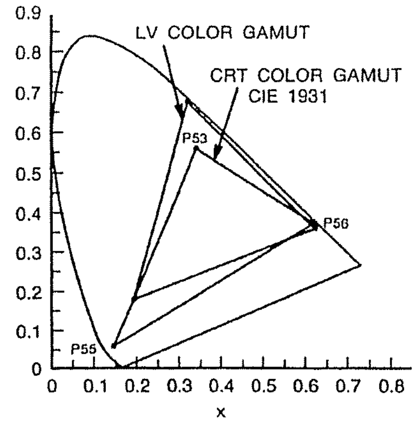

Figure 6.35 Color gamut of Seiko-Epson AMLCLV projection display (Morozumi et al., 1986) and CRT projection display.

lossy areas are the collection efficiency of the lamp (which is very good if it is 50%) and the transmission of the light valve. The active matrix transmits about 60%, and the light valve and substrate reduce transmission further, until total transmission through a light valve is on the order of 5–30%. Optics transmission of the light valve system includes the efficiency of the dichroic beam-splitting and -combining components as well as the projection optics transmission. Typical systems use 150–300-W tungsten or metal halide lamps, achieving between 100 and 300 lumens out of the projection optics.

One major advantage of an active-matrix liquid-crystal light valve display is the ease of convergence. The image geometry is controlled by the pixel geometry, which is fixed. The individual pixels do not move with respect to each other, and become nonlinear. Two light valve pixel geometries that are manufactured identically need only initial mechanical alignment and will stay converged thereafter.

Active-matrix LCLV projectors operate at video rates with sufficient modulation and contrast to provide video images. These systems have expanded the applications for projection displays, as they have provided a small-size projection display suitable for video and data presentation on screen sizes in between those of direct-view and projection CRTs. The smallest screen size available with CRT projection systems is about 40 in. diagonal, whereas AMLCLV projectors can project onto screens as small as 20 in. and are much smaller, lighter, and less expensive than CRT projection displays. Figure 6.36 compares the size of an active-matrix LCLV video projector with that of a CRT video projector. The light

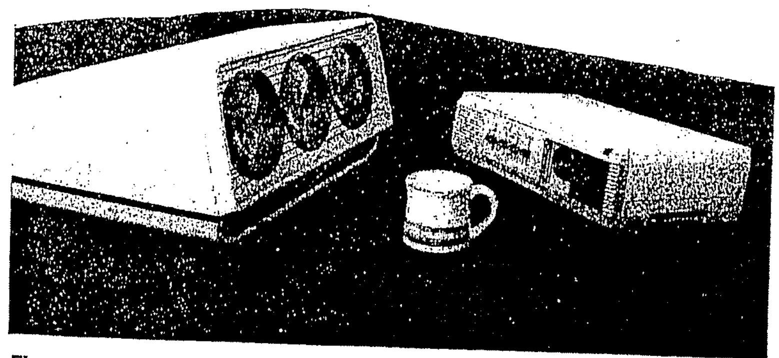

Figure 6.36 Comparison of Sony CRT projection display (left) and Kodak/Seiko-Epson AMLCLV projection display (right).

valve systems do not yet reach into the higher performance end of the CRT systems but have considerably expanded the applications for projection systems in smaller screen sizes and have the potential to increase their capabilities substantially.

6.4.2 Optically Addressed LCLV Projection Displays

Optically addressed LCLVs combine the attributes of a high-luminance white-light source and a high-resolution, low-luminance image source. A high-resolution image generator, such as a CRT, is used to modulate high-intensity white light, achieving higher luminance than that possible by magnifying the CRT image. The larger sizes and higher cost of these displays limit their use to high-performance applications.

Operating Principles of Optically Addressed LCLV Projection Displays

Optically addressed liquid-crystal light valves are used in a reflective mode, as shown in Figure 6.31. In this configuration an optical image is written onto one side of the light valve. The image source is most commonly a CRT but can be a scanned laser image or other image source. A high-luminance white-light source is used to supply polarized light to the side opposite the writing side of the light valve. The light valve varies the polarization of the reflected light in proportion to the luminance of the written image. A polarizer/analyzer pair turns this polarization modulation into a gray-scale image that is projected onto a screen.

Hughes Aircraft Company (HAC) designed, developed, and marketed a reflective liquid-crystal light valve that works in this manner (Efron et al., 1981; Grinberg et al., 1975). They also developed projection displays that use the liquid-crystal light valve (Bleha et al., 1977; Ledebuhr, 1986; Fritz, 1990).

The structure of the Hughes LCLV is shown in Figure 6.37. The light valve combines an ac-driven photoconductor/dielectric mirror substrate with a nematic liquid crystal operated in the voltage-controlled birefringence mode. Between two transparent conductive electrodes of indium tin oxide are a photoconductor, a light-blocking layer, a dielectric mirror, and a liquid-crystal layer. The image is written on the photoconductor side. An ac bias voltage is applied between the transparent electrodes. Where there is no image light impinging on the photoconductor, the ac bias voltage is primarily across the photoconductor and not the liquid crystal. When an image pixel is on, light impinges on the photoconductor, the impedance at that point drops, and the voltage is across the liquid crystal. This voltage across the liquid-crystal layer is used to vary the birefringence of the layer.

Polarized illumination generated by a xenon arc lamp enters the projection side of the light valve. It passes through the liquid-crystal layer, reflecting off the dielectric mirror and back through the liquid-crystal layer before exiting the light valve. Voltage across the liquid-crystal layer varies the birefringence of the layer,

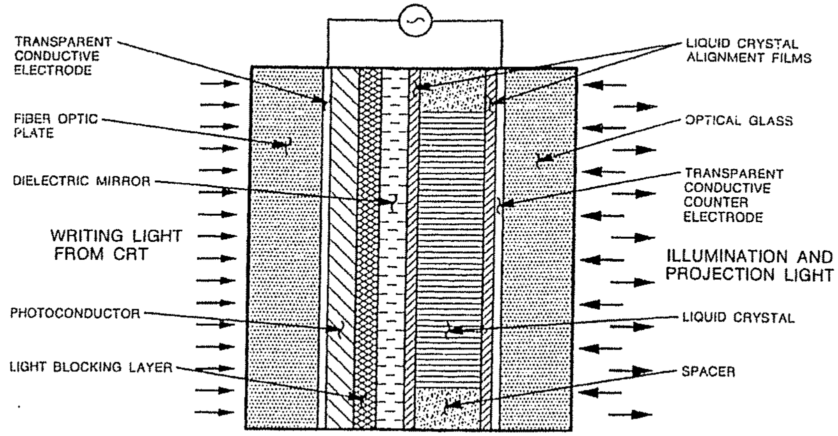

Figure 6.37 Structure of Hughes Aircraft Company optically addressed LCLV (Gold and Ledebuhr, 1985).

which alters the plane of polarization of the reflected light as it passes through the liquid crystal.

No image light impinging on the photoconductor results in projection illumination exiting the LCLV in the same polarization state as it entered and being blocked by the polarizer/analyzer (Fig. 6.38).

Image light impinging on the photoconductor results in a voltage drop across the liquid crystal. Projection illumination emerges with a polarization that is rotated 90° to the incident light and passes through the polarizer/analyzer. This full "on" condition of the light valve is illustrated in Figure 6.39.

Light levels and resulting voltage gradations between full on and full off create the gray scale of the image.

The projection display systems that Hughes has marketed use a CRT to write the image onto the light valve, but other sources are feasible. A display system has been fabricated that uses a scanning laser beam to write the image (Trias et al., 1988).

Characteristics of Optically Addressed LCLV Projection Displays

Full color is created by using three different light valves, one each for red, green, and blue image light, as in the active-matrix-addressed LCLV display. Figure 6.40 illustrates the layout of a full-color Hughes projection display using three optically addressed LCLVs and CRTs to provide the writing image.

The luminance of a display using the Hughes LCLV is dependent on the lamp

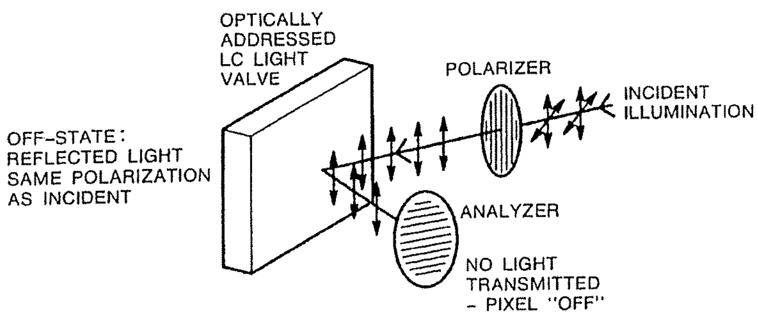

Figure 6.38 Optically addressed LCLV in "off" state.

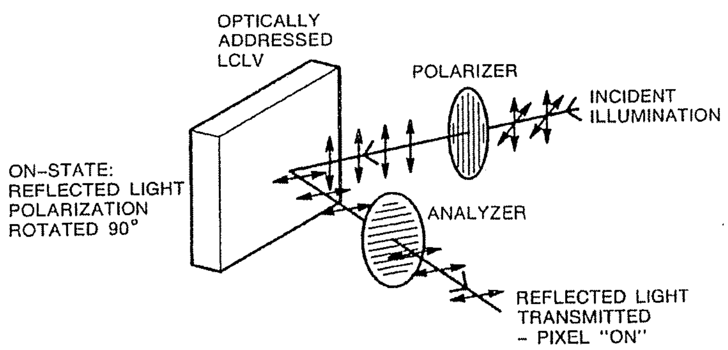

Figure 6.39 Optically addressed LCLV in "on" state.

efficacy, collection efficiency, optical system transmission, and light valve transmission [Eq. (6.4)]. A range of systems are available, with varying xenon lamp sizes and performance characteristics. Lamp sizes run from 500 to 2000 W, with resulting outputs up to 2500 white lumens.

The resolution of these systems is 1024 visible scan lines × 1400 pixels per line, with contrast ratios reported to be 50:1 (Fritz, 1990).

The systems presently being produced use a cadmium sulfide photoconductor, which is operated at 30 Hz interlaced video rates but is not as fast as desired.

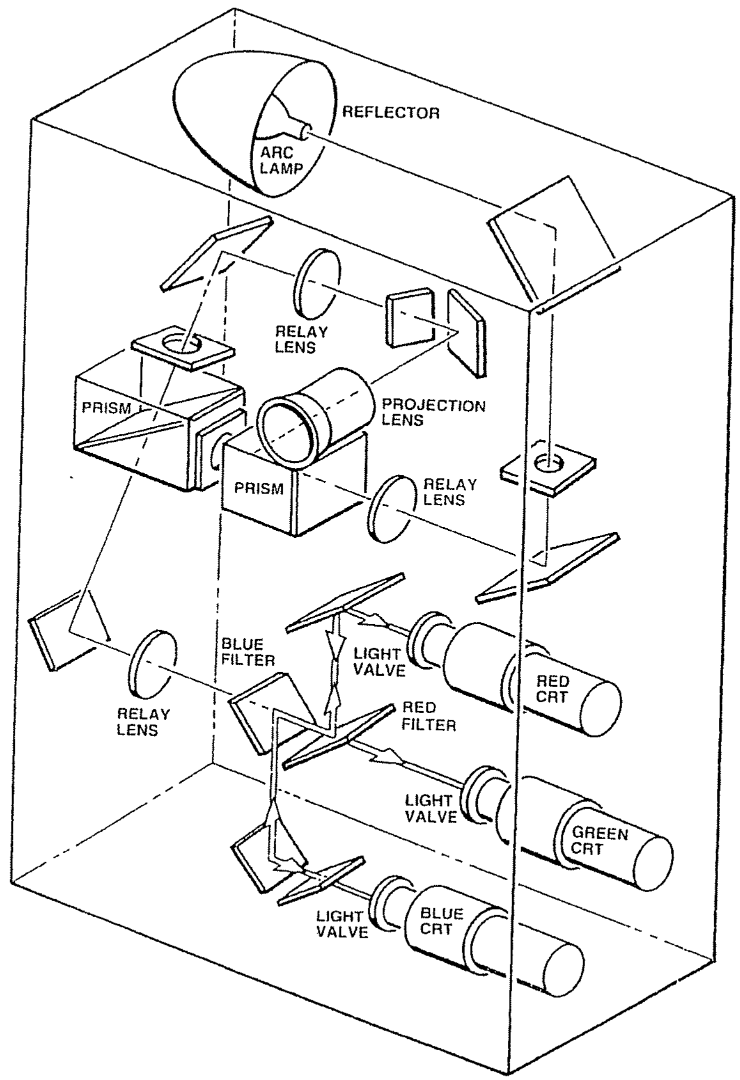

Figure 6.40 Layout of full-color projection display using Hughes optically addressed LCLV (Ledebuhr, 1986).

Recently, a new light valve design was reported (Sterling et al., 1990) that uses an amorphous silicon photoconductor, promising faster operating speeds.

The geometry and linearity of the image are determined by the writing CRT, so the convergence and registration techniques are the same as for a CRT system (Section 6.7). The Hughes displays use an active convergence feedback technique to provide misconvergence detection and correction.

Optically addressed LCLV systems are used to provide high-performance large-screen displays for commercial and military/aerospace environments. The systems are used with screen sizes ranging from 1 to 5 square meters. Ruggedized versions of these systems are being used in naval shipboard applications (Fritz, 1990; Gold, 1980). Other applications include large-screen command and control (Gold and Ledebuhr, 1985) and simulation applications (Sterling et al., 1990). Figure 6.41 pictures a projection display system using the Hughes optically addressed LCLV. This system is 24 in. wide × 72 in. high × 44 in. deep.

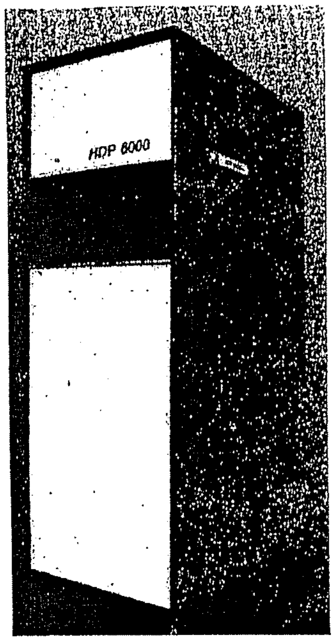

Figure 6.41 Picture of Hughes Aircraft projection display using CRT-addressed LCLV. This system is 24 in. wide, 72 in. high, and 44 in. deep. (Photo courtesy of Hughes Aircraft Co., Fullerton, Calif.)

6.4.3 Thermally Addressed LCLV Projection Displays

Thermally addressed LCLVs are used to create full-color systems capable of displaying very high density alphanumeric and graphic data, such as maps or large CAD and engineering drawings. This extremely high resolution capability is the principal advantage of thermally addressed LCLV projection displays. In a situation similar to optically addressed LCLV displays, a high-resolution image source—in this case a deflected IR laser beam—is used to create the image and modulate a high-luminance white-light source. Thermally addressed LCLVs do not operate at video rates, however, and this low speed is the main disadvantage of such displays, limiting their use to applications where real-time speeds are not needed.

Operating Principles of Thermally Addressed LCLV Projection Displays

A smectic liquid-crystal light valve can be designed to have two different states: a transparent state and a scattering state. Smectic liquid crystals exhibit a hysteresis effect, and the present state depends on its history and temperature (Kahn, 1973). In a display application the temperature is controlled to be slightly below the transition temperature where the cell turns from clear to scattering. Local heating causes local areas of scattering, which has little effect on neighboring areas, and so will have very sharp edges. This is illustrated in Figure 6.42.

The thermally addressed LCLV is used in a display application in a reflective mode, with an IR laser providing the writing illumination and a white-light source providing the projection illumination (Fig. 6.43). The IR laser (usually a

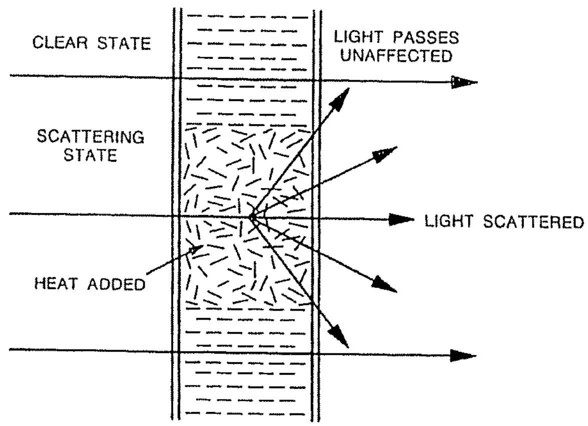

Figure 6.42 Scattering and clear states of smectic liquid-crystal light valve.

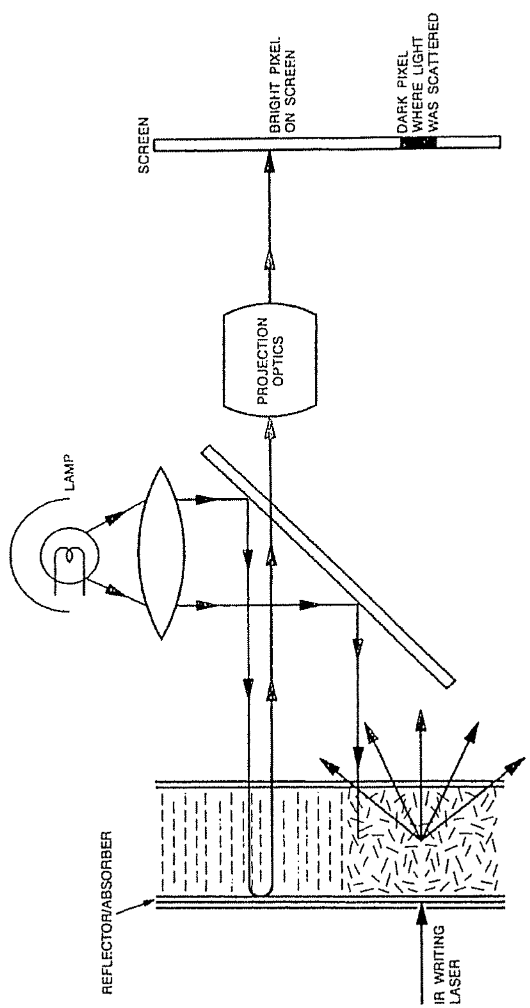

Figure 6.43 Layout of projection display using thermally addressed LCLV.

laser diode) is modulated with video information and deflected across the light valve to write the image (laser modulation and deflection techniques are covered in Section 6.5). Coatings on the light valve reflector/absorber are designed to absorb IR laser light, which heats the liquid-crystal material, while reflecting projection light.

Wherever the IR laser beam writes onto the light valve, the region undergoes local heating, which turns that region (pixel) into a scattering state. Illumination light hitting the liquid crystal is highly scattered, with little light being accepted by the projection lens. This creates a dark pixel on the screen where the laser writes on the light valve. In unwritten areas, the liquid crystal is transparent. Projection illumination reflects off the light valve unaltered and is collected by the projection optics and imaged onto the screen, creating a bright pixel.

The light valve has a semipermanent memory. After being written, an image remains until erased or updated. A local change requires only local erasing and rewriting, as opposed to rewriting the entire image.

Characteristics of Thermally Addressed LCLV Projection Displays

Just as with other LCLV projection displays systems, color is implemented by using multiple monochrome light valves, and the color gamut is largely determined by the spectral characteristics of the dichroic filters used to separate the white light into components.

The resolution capability of thermally addressed LCLV projection displays is unmatched by other types of projection displays. These systems have been under investigation by several companies (Dewey, 1984; Tsai, 1981). Several systems are offered as products: the Hitachi liquid-crystal large-screen display and the Greyhawk Softplot and LAD systems. The Hitachi system (Nagae et al., 1986) projects an image with an addressable resolution of 2000 × 2000 pixels onto a 6.5 ft × 6.5 ft screen, with a resulting image luminance of 40 fL. Greyhawk has several systems (Stepner and Kahn, 1986; Kahn et al., 1987), including the Softplot, a 40-in. diagonal display with a resolution of 3400 × 2200, and the LAD (large-area display) system with a 7 ft × 10 ft screen and 5000 × 7500 pixels. Figure 6.44 pictures the Greyhawk LAD display.

These systems are used for static images, with writing times for a whole screen ranging from 30 secs to 30 min. Particular areas can be erased and rewritten, allowing interactive changes and updates.

Thermally addressed LCLV displays are used for displaying and checking circuit diagrams and engineering drawings; for displaying maps, networks, and command and control information; for displaying and monitoring plant operations; and for displaying other high-information-content static images, which alternatively must be plotted out on hard copy to view. Their resolution is higher than other projection display systems considered in this chapter, but video rate operation is not possible at this time.

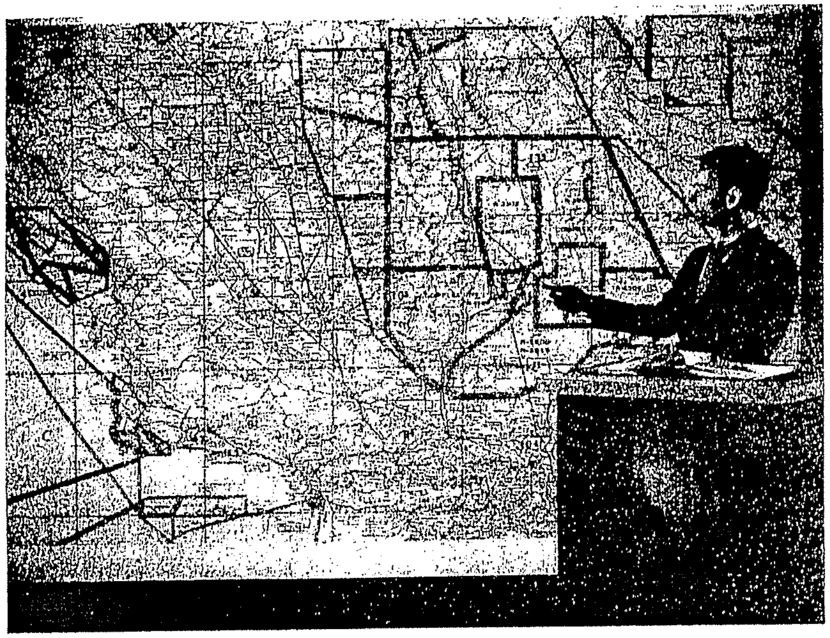

Figure 6.44 Picture of Greyhawk LAD projection display using thermally addressed LCLVs. (Photo courtesy of Greyhawk Systems, Inc., Milpitas, Calif.)

6.4.4 Liquid-Crystal Light Valve Projection Displays: Summary

Liquid-crystal light valves are implemented into display applications using a variety of addressing techniques, including active-matrix addressing, optical addressing, and thermal addressing. These displays have in common the advantage that their resolution and luminance are not interrelated. Besides this common advantage, each type has its own distinguishing characteristics. Active-matrix-addressed LCLV projection displays have added a new class of small, lightweight, low-cost video projectors competing with CRT projection displays. Optically addressed LCLV projection displays are high-luminance, high-resolution systems but are also large and relatively expensive. Thermally addressed LCLV projection displays possess resolution characteristics unmatched by other projection displays but are not currently capable of operation at video rates.

6.5 LASER PROJECTION DISPLAYS

A laser projection display creates an image by writing directly onto the projection screen with a laser beam. The laser light is diffused by the screen, making the real image visible to the viewer. Laser displays possess several inherently high-quality aspects: the fully saturated colors, the high-resolution capability of a focused laser beam, and the high luminance and contrast capability of lasers. Laser displays have not achieved a large amount of commercial success, primarily because of the size and inefficiency of lasers themselves. Recent progress in small visible lasers is creating practical alternatives to the larger lasers.

6.5.1 Operating Principles of Laser Projection Displays

In a laser projection display the image is written on the viewing screen with a scanning laser beam, very much like an image is written on a CRT with an electron beam. The screen does not luminesce, however; instead, the laser light is diffused by the screen, which is placed at the real-image location. The basic components of a laser projection display, shown in Figure 6.45, are the laser light sources; the modulators, which encode the laser beam with intensity variations corresponding to the video information; the deflectors, which provide movement of the laser beam to trace out the image on the screen; and the screen itself.

Monochrome laser projection displays use a single laser. To create a full-color laser display, one laser for each color is used. It is possible to obtain "white" lasers, which combine several lasing sources into a single package.

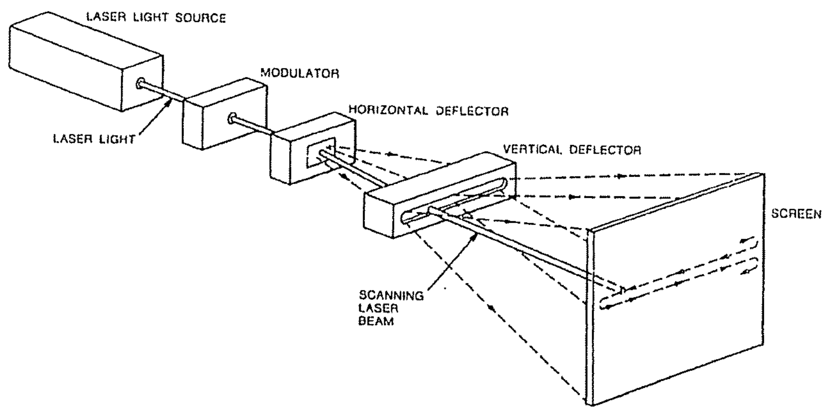

Figure 6.45 Laser projection display components.

Historically, laser projection displays have used argon-ion lasers for the green and blue colors and either a krypton laser or an argon-ion pumped dye laser for red. These lasers are inefficient, and to obtain the watts of output power required, water-cooled lasers requiring kilowatts of input power are necessary. This has limited the use of laser displays to extremely large image size systems, such as concert hall and laserium displays.

Recent developments in diode lasers and diode-pumped solid-state lasers hold the potential to open up the range of applications for laser projection displays. Diode lasers have seen their introduction into visible wavelengths and have been steadily increasing in power and decreasing in wavelength. Moreover, diode-pumped solid-state lasers are providing visible light with efficiencies that are orders of magnitude greater than that of argon-ion and dye lasers. These small, efficient, visible lasers have the potential to make small laser displays a reality. Figure 6.46 is a picture of a small 532-nm diode-pumped solid-state laser.

Video information is encoded into the laser beam with a modulator synchronized with the scanning mechanism. There are numerous methods that can be used to modulate a laser beam (O'Shea, 1985), the most common being an acousto-optic modulator.

An acousto-optic (A-O) modulator uses an acoustic signal to create a bulk diffraction grating in a crystal (Yariv and Yeh, 1984). This is accomplished by using the acoustic wave as a pressure wave applied to the crystal, which creates

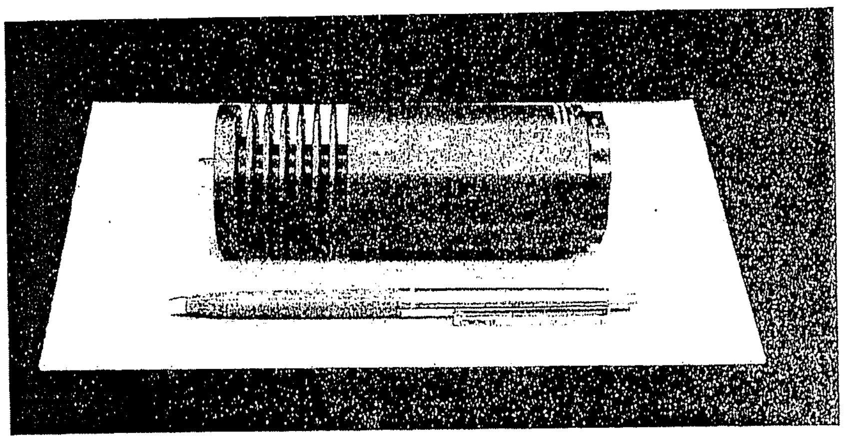

Figure 6.46 Picture of Amoco laser diode-pumped solid-state laser with 532-nm output.

a periodic variation of the index of refraction within the crystal. This is seen by a laser beam passing through the crystal as a bulk diffraction grating.

Acousto-optic modulators operate in the Bragg regime (Lekavich, 1986), where, at the particular Bragg incidence angle, most of the light is diffracted into the first order. The diffraction efficiency (percentage of light diffracted into the first order) depends on the amplitude of the acoustic driving signal. Laser beam modulation is implemented by varying the amplitude of the acoustic drive signal, which in turn varies the amplitude of the light passed to the first order (Fig. 6.47). The zero order is blocked, while the modulated first order travels through the rest of the system and onto the screen.

Laser beam deflection can be accomplished by one of several means, depending on the speed, size, and accuracy desired. Deflection techniques include mechanical mirror deflection (specifically rotating polygon, galvanometer mirror, and hologon deflection) and acousto-optic deflection.

A rotating polygon with mirror facets is used when repetitive scans at a fixed frequency are desired. A motor rotates the polygon, and the laser beam reflects off the mirrored facets. As the polygon rotates, the angle of incidence of the laser beam is changed, which in turn changes the angle of reflection, and the laser beam traces out one line for each facet. As the polygon continually rotates, the laser will continuously trace out a horizontal line (Fig. 6.48). The polygon is

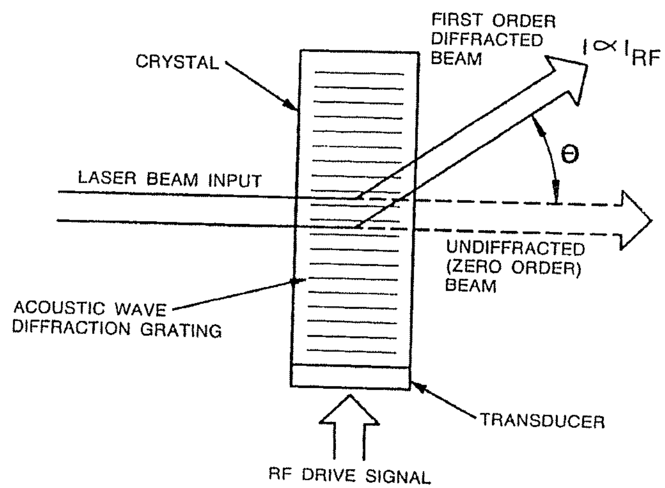

Figure 6.47 Principles of acousto-optic laser modulation.

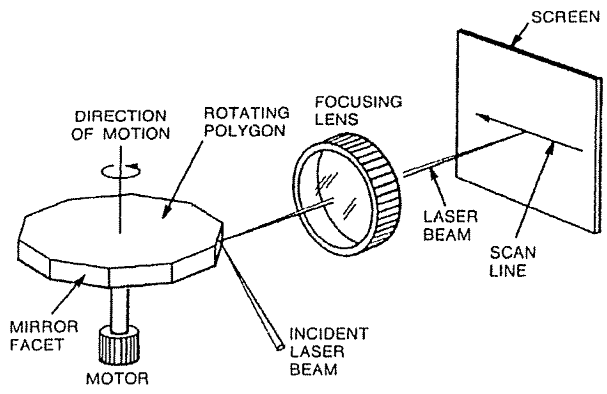

Figure 6.48 Rotating polygon laser deflection.

commonly used in laser raster projection displays to provide horizontal deflection.

Polygon deflection frequency depends on the revolutions per minute of the polygon and the number of facets on the polygon. In general, very high speeds, and very high resolutions, can be achieved with the rotating polygon. In display applications, a polygon mirror is used for the horizontal deflector in raster displays with addressabilities ranging from 525 scan line TV systems to HDTV systems running at 1125 scan lines. The performance trade-off is that of speed versus size. To provide many scan lines, the number of polygon facets can be increased, but this results in an increase in polygon size and in power required. Alternatively, the polygon rotational speed can be increased, providing a smaller polygon, but there is a limit to how small and how fast a polygon can be operated.

A new twist on the rotating polygon is the rotating hologon, which uses holographic segments to reflect the laser beam as the hologon turns (Fig. 6.49). The holograms are quite easy to replicate, making their production costs low. An example of a popular use of hologons is in supermarket scanners.

A galvanometer deflector uses a moving coil principle to provide single-axis rotation of a mirror, which in turn deflects the laser beam, as shown in Figure 6.50. Galvanometer mirrors are commonly used in a random access mode for large outdoor laser displays in stadiums, amusement parks, or concert halls. They are also used in a resonant mode to provide a raster deflection pattern. The speed of deflection is limited to below about 25 kHz, so this type of deflector is commonly used as the vertical deflection device in raster laser projection displays.

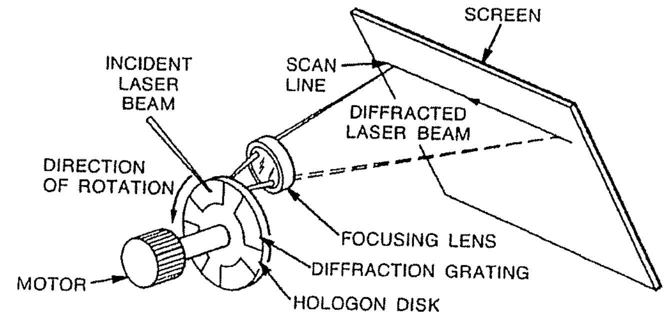

Figure 6.49 Rotating hologon laser deflection.

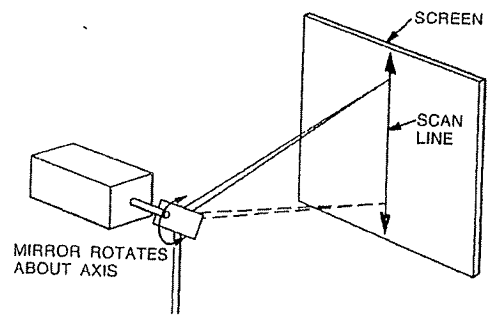

Figure 6.50 Galvanometer mirror laser deflection.

Acoustic-optic deflectors work very similarly to acousto-optic modulators. A refractive index grating is created in a crystal with an acoustic wave. Laser light incident at the Bragg angle diffracts into a strong first order. For deflection to occur, the frequency of the acousto-optic wave is changed, which varies the angle of diffraction of the first order (Fig. 6.51), causing the laser beam to trace out a line. This type of deflection is commonly used for the horizontal deflection in a raster laser display.

The acousto-optic modulator and deflector are very similar in operation, the difference being that the A-O modulator varies acoustic drive *amplitude* to modulate the first order, and the A-O deflector varies acoustic drive *frequency* to deflect the first-order beam.

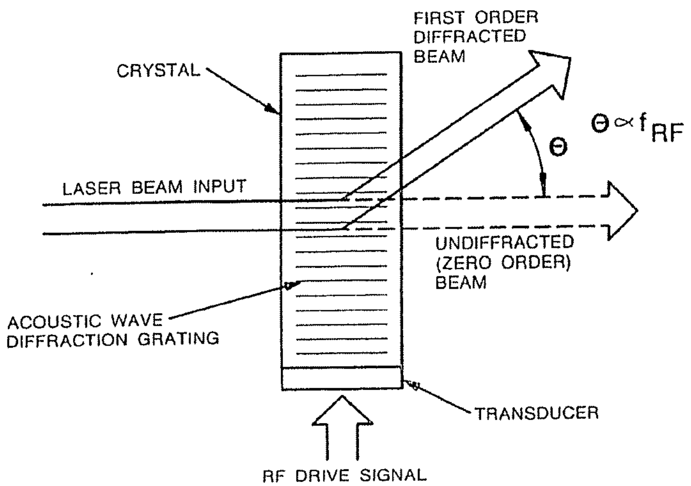

Figure 6.51 Acousto-optic laser deflection.

There are numerous methods for implementing these scanning and modulating components in a laser projection display (Hubin, 1991; Johnson and Montgomery, 1976; Merry and Bademian, 1979) and design rules that help determine the best method for a particular application (Beiser, 1974, 1986; Zook, 1974; O'Shea, 1985).

Laser video displays typically consist of an acousto-optic modulator, a galvanometer mirror for vertical deflection, and either a polygon mirror or an acousto-optic deflector providing the horizontal deflection. Figure 6.52 shows the configuration of a system using a polygon mirror, and Figure 6.53 gives the configuration for a system using an acousto-optic deflector.

Speckle is a phenomenon unique to laser systems, occurring because of the coherent nature of laser light. Speckle is the sparkling/granularity effect visible in laser images, which comes about from the interference of the coherent laser beam with itself after passing through or reflecting off a diffuse screen. The coherent laser beam is redirected by the screen, and then different parts of the beam interfere with each other to set up an interference pattern in space. The positive and negative interference regions cause light and dark spots to appear in the image, which move as the viewer moves within the viewing volume (because the pattern is not on the screen, it is in space). This movement of the speckle pattern causes the sparkling effect.

Speckle is present in most laser displays, including those that are rastered and/

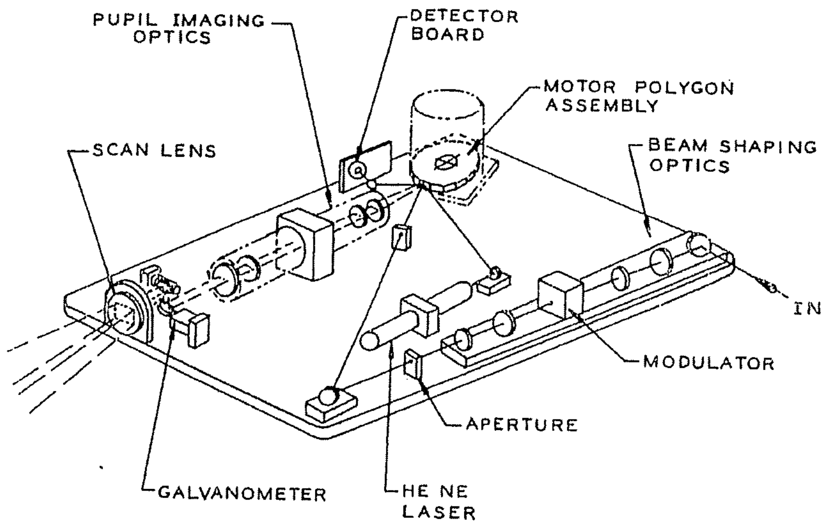

Figure 6.52 Layout of the Lincoln Laser RS-3A laser raster video display utilizing polygon horizontal deflection. The He-Ne laser is used to derive sync signals for the system. (Courtesy of Lincoln Laser Corp., Phoenix, Ariz.)

or full-color or multicolor laser displays. Its presence is noticed less at lower luminance, and it can become quite brilliant at higher luminances. The principle behind speckle-removal techniques is to either remove the coherency of the light or to overlay many different speckle patterns in space so that they average out to be a smooth image (Welford and Winston, 1989). The most common speckle-removal technique is to place a moving diffuser at an intermediate image plane, which overlays multiple interference patterns at the viewing plane image.

6.5.2 Characteristics of Laser Projection Displays

The color gamut of a particular laser display depends on the wavelengths of the lasers used in the system. The color gamut of laser displays is typically larger than that of other display types because the colors are fully saturated, lying on the outside of the chromaticity diagram, as shown in Figure 6.54. Changing the laser wavelengths slides the triangle corners along the outside of the CIE diagram.

The resolution of a laser display depends on the electrical bandwidth of the laser modulator, the speed of the scanning device, and the smallest spot that the

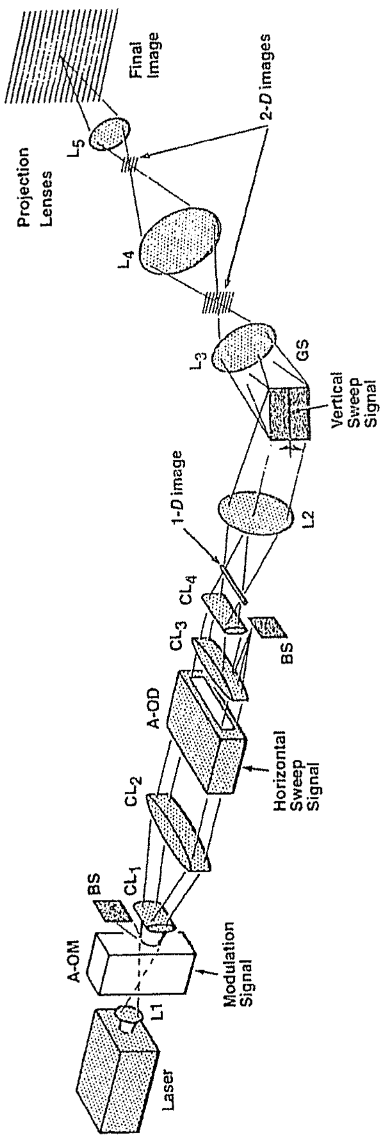

Figure 6.53 Components of laser projection display using acousto-optic horizontal deflection (A-OD) and acousto-optic modulation (A-OM) (O'Shea, 1985). BS = beam stop, CL = cylindrical lens, and L = lens.

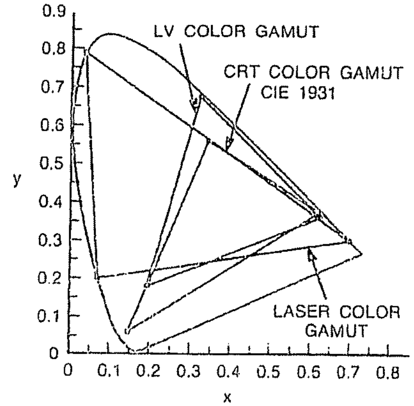

Figure 6.54 Color gamut of laser projection display, using green at 514 nm, red at 647 nm, and blue at 488 nm.

laser display can be focused to. Owing to its coherent nature, laser light can be focused to a very small spot. This focused spot can be so small that in practice the laser beam may have to be defocused because scan lines are visible. The laser beam can also be collimated so the distance to the screen does not affect focus. This characteristic can be very desirable and is unique to laser displays. The speed of the scanning device and resulting system resolution depends on the particular scanning device and implementation.

The luminance of a laser display depends on the laser power used and the light throughput of the display system.

$$B_S = W_{laser}\eta_{laser}T_{system}\, G/A \tag{6.5}$$

where W_{laser} is the power out of the laser in watts; η_{laser} is the luminous efficacy of the laser, in lumens per watt; and T_{system} is the system transmission. The system transmission depends very much on the deflection system used, varying anywhere from less than 5% to over 50%. Acousto-optical components are not as efficient as mirrors, so the more A-O components in a system, the lower the transmission. However, A-O components are compact and have no moving parts, a desirable feature in many applications.

Laser displays can operate at video rates, with modulation, contrast, and speed consistent with these requirements. Unlike many other display systems, the laser display has no persistence or memory.

Convergence must be addressed in color laser displays, as with other projection displays. This is very often handled with photosensor devices that pick off a

portion of light to determine the amount of misconvergence, providing feedback to a mirror or deflector that performs correction. Convergence techniques are discussed further in Section 6.7.

The size, weight, and power consumption of laser displays vary widely. Since the most common application of laser displays is to create images larger than any other projector is capable of handling, the systems tend to be large and power-hungry. Entertainment establishments such as Disneyland and SeaWorld use laser displays to provide large-scale visual effects unobtainable with other light and image sources.

Although the most common application of laser displays is for very large custom displays, several companies have marketed laser displays for applications where the screen size is less than 25 ft. The Naval Training Equipment Center has been very successful in implementation of a laser display for a flight simulator (Barber, 1984). Several small 525-line systems are available, such as the IntraAction system shown in Figure 6.55. This system is a monochrome projector using an A-O modulator, an A-O horizontal deflector, and a galvanometer mirror vertical deflector.

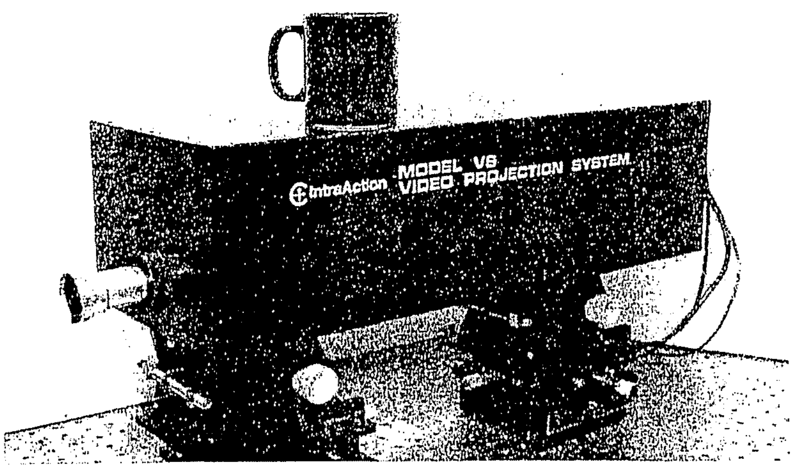

Figure 6.55 Monochrome laser video projection display (IntraAction Corp., Bellwood, Ill.).

6.5.3 Laser Projection Displays: Summary

Laser projection displays write an image directly onto the projection screen with one or more laser beams. Laser projection displays have several high-quality aspects due to the coherent, monochromatic nature of laser light, such as high resolution and a large color gamut. The large size and inefficiency of the laser light sources have kept these displays from becoming very popular, but recent advances in small, efficient visible lasers promise new territory for laser projection displays.

6.6 PROJECTION DISPLAY SCREENS

6.6.1 Introduction

The projection screen is a very important part of the projection display. A high-quality, high-resolution image source and projection optical system can be degraded by a projection screen that does not preserve the image quality of the display.

This chapter covers screens placed at the real image plane of the projection system as diffusers to view the image. Virtual image displays and the "screens" used with them do not fall into this category.

The characteristics of the projection screen can determine the final image quality of the displayed image, including luminance, resolution, contrast, and color. The goal of a projection screen design is to present the projected image to the viewer with little to no image quality degradation within a specified viewing volume. This is accomplished by using various types of diffusion and lens action, including refraction and reflection provided by lenslets, diffusion by scattering centers, and absorption from dyes.

Projection screens are usually designed to be used as either a front projection screen or a rear projection screen, usually not both. These two types of screens are shown in Figures 6.2 and 6.3. Front projection screens reflect the projection light into the viewing volume. Rear projection screens transmit the projected light through the screen to the viewer. Two advantages of front projection are that the screen can be curved to provide gain, and no projection space is needed behind the screen. The advantages of rear projection screens are that less ambient illumination is directed into the viewing volume and the display can be made more compact by folding.

Front projection used to be the more popular and still is for large auditorium presentations where the room is relatively dark. Rear projection has become the more popular implementation for home TV systems and other applications where ambient illumination may be a problem.

Front and rear projection screens are characterized by the same parameters: gain, reflectance, colorimetry, and contrast under ambient illumination. These

parameters are measured and given in terms of bend angle. The bend angle is the angle through which a principal ray of light from the projector must bend, as it hits a point on the screen, to get directed into the viewer's eyes. The viewing angle, sometimes confused with the bend angle, is the angle between the viewer's line of sight and the normal to the screen. If the viewer is looking at the center of the screen, then the viewing angle is equivalent to the bend angle. Figures 6.56 and 6.57 illustrate these concepts.

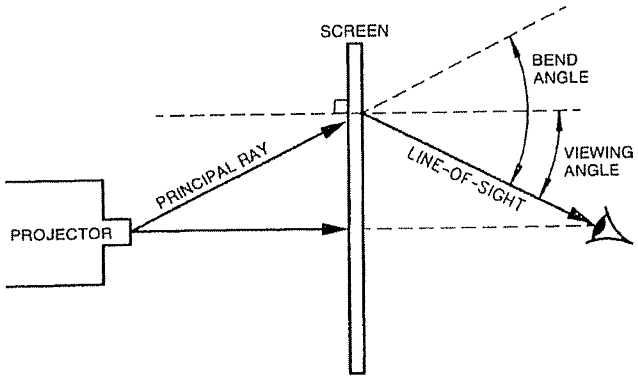

Figure 6.56 Bend angle vs. viewing angle.

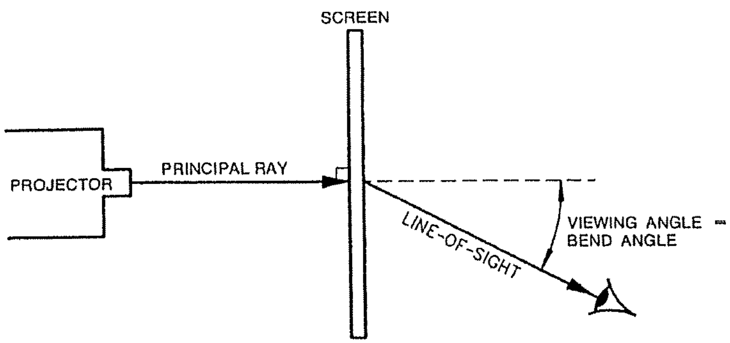

Figure 6.57 The bend angle is equivalent to the viewing angle when the viewer looks at the center of the screen.

The viewing zone of a particular projector–screen combination is that range of angles wherein the image quality, including luminance, resolution, and contrast, falls within specified parameters.

6.6.2 Screen Types

The number of types of screens available for use with projection displays has expanded greatly in recent years. In addition to standard diffusion techniques to create a real image, optical elements have been added to the screens to direct the light and tailor the viewing zone in such a way that little light is wasted. Screens are now available with lenticular lenslets, Fresnel lenses, and contrast-enhancing black stripes in addition to the diffusing element. These elements combine to make the screen a highly developed optical system.

Diffuse screens, those that use only diffusion to create an image and a viewing zone, include front diffuse screens, rear diffuse screens, flexible diffuse screens, and rigid diffuse screens. This screen category includes ground glass and opal glass. There is an extremely wide range of types of diffusion and the resulting characteristics.

Flexible diffuse screens have a diffusing coating applied to a vinyl substrate. They are low-cost and lightweight and can be made in very large sizes. Flexible diffuse screens can be rolled up when not in use. Some flexible diffuse screens can be used for both front projection and rear projection applications. Flexible screens are sometimes dyed to add contrast or have holes perforated in them to let sound through. A major drawback to flexible diffuse screens is that they are subject to motion during use as a result of air currents or pressure differentials within the environment, causing unwanted image distortions.

Rigid diffuse screens can be fabricated from glass or plastic, with either bulk or surface diffusion added. Surface diffusion is created by grinding, acid etching, or coating the surface of a glass or acrylic substrate. Bulk diffusion is created by adding particles within the substrate, which cause progressive diffusion as the light travels through the screen (Goldenberg and McKechnie, 1985). Rigid diffuse screens include ground glass, opal glass, and marata plates, among others.

Fresnel lenses are used with rear projection screens to direct the rays falling on the screen's outer edges toward the viewer. This helps create an image with even luminance across the screen, avoiding image luminance rolloff at the edges. The operation of a Fresnel lens used with a diffuse rear projection screen is illustrated in Figure 6.58.

Lenticular lenslets are used with both front and rear projection screens to tailor the light distribution. Von Rolf Moller first discussed the use of lenticular screen elements in 1939 (Moller, 1939). The lenslets are usually cylindrical, although both spherical and toroidal lenslets have been discussed and demonstrated (Henkes, 1982; Mihalakis, 1987; Takatsuka et al., 1982). The lenslets use both reflection and refraction to distribute image light into a particular viewing zone.

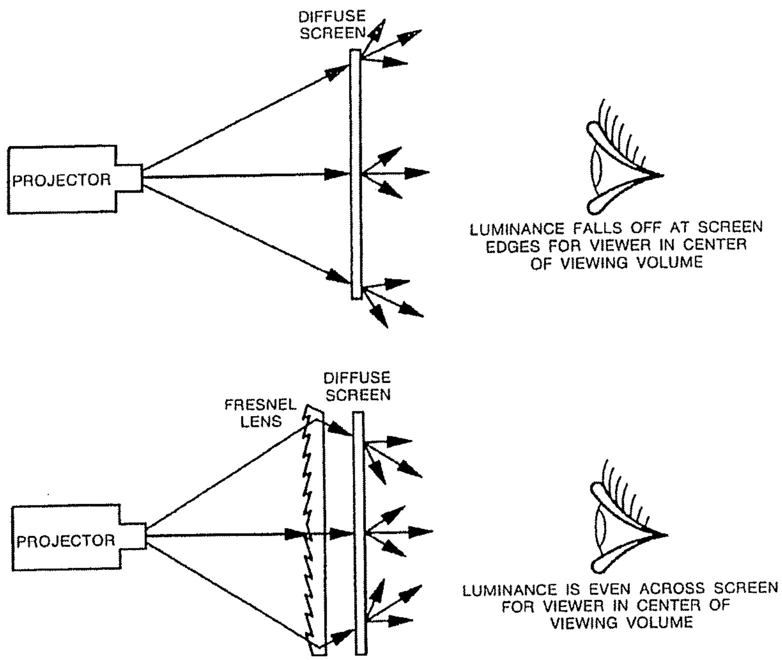

Figure 6.58 Action of Fresnel lens with rear projection screen.

Their most common implementation is to widen the image viewing zone in the horizontal direction while not affecting the vertical (Fig. 6.59). Recent designs have also implemented lenslets that account for color separation caused by off-axis CRTs.

Lenticular structures in a rear projection screen may include black stripes, which are used to absorb ambient illumination and lower the overall reflectance of the screen (Bradley et al., 1985). Lenslets are used to direct image luminance away from the black stripes but allow ambient illumination to be absorbed.

High-performance projection screens have become complex and detailed systems. The screens used with consumer projection TVs consist of a Fresnel lens, a diffusion layer, at least one set of lenticular lenslets, and black stripes. Figure 6.60 shows an example of a complete screen structure using all of these elements.

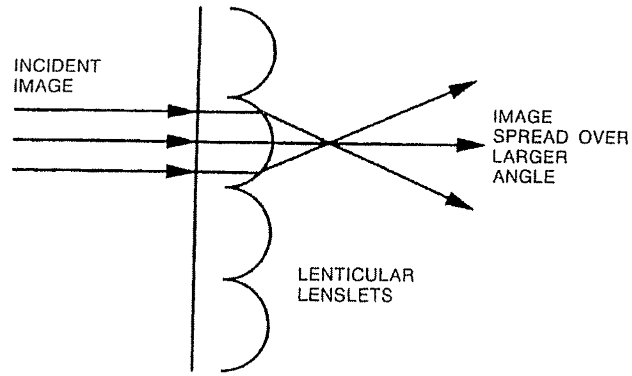

Figure 6.59 Action of lenticular lenslets.

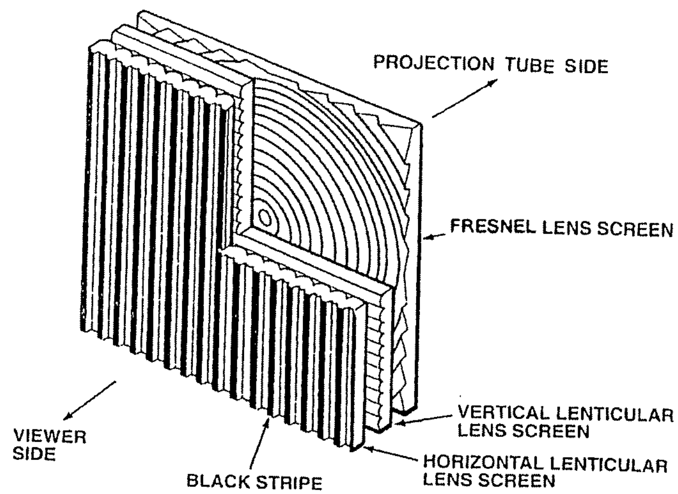

Figure 6.60 Structure of rear projection screen using Fresnel lens, horizontal and vertical lenticular lenslets, and black stripes (Murakami et al., 1989).

6.6.3 Screen Characteristics

Gain is a measure of the relative luminance of an image provided by a particular screen and is probably the most important and most commonly used measure of comparison between screens. Screen gain curves describe the relative image luminance versus bend angle provided by a particular screen. The *gain* of a screen is defined to be its luminance at a given angle relative to the luminance that would be achieved if a Lambertian screen were used:

$$G(\theta) = B_S(\theta)/B_L \tag{6.6}$$

where $G(\theta)$ is the screen gain as a function of bend angle, $B_S(\theta)$ is the screen luminance as a function of angle, and B_L is the luminance that would be achieved if the screen were Lambertian. A Lambertian screen is considered to be perfectly diffuse, diffusing light into all angles with equal luminance, and its luminance is therefore not angle-dependent. Figure 6.61 illustrates the viewing zone of a perfectly diffuse Lambertian screen, defined to have a gain of 1 at all angles.

The gain of a screen is often referred to and used in calculations without its angle dependence, which implies that the on-axis (0°) angle is being used.

Gain versus bend angle curves show how a screen distributes the image luminance. A screen with a gain greater than 1 at a particular angle directs more light to that direction than a Lambertian screen would. Conservation of energy cannot be violated, of course, and so a screen with high gain at some angles must have lower gain at other angles. Figure 6.62 shows the viewing volume of a screen with a gain greater than 1 at many angles.

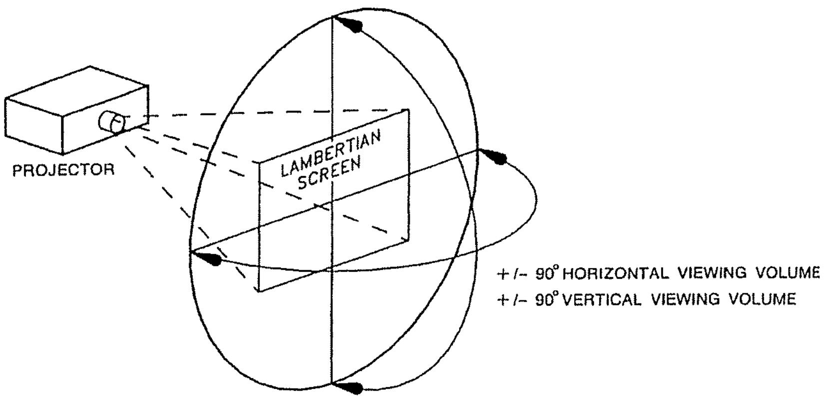

Figure 6.61 Lambertian screen viewing volume (gain equals 1 at all angles).

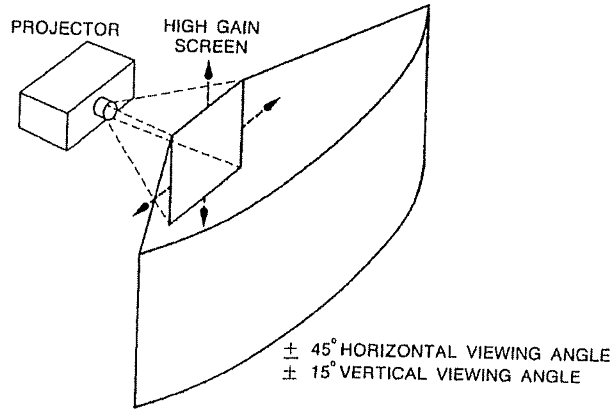

Figure 6.62 High-gain screen viewing volume.

Figure 6.63 shows the gain curves for a set of six different rear projection screens: two rigid diffuse, two flexible diffuse, and two composite screens. The composite screens each consist of a Fresnel lens, a diffuser, and a set of lenticular lenslets. The high-gain screens provide high luminance on-axis, but the luminance falls off rapidly, resulting in a smaller viewing volume. The lower gain screens have a lower luminance on-axis, with a correspondingly larger viewing volume.

Composite screens do not have the same gain curves in the horizontal and vertical directions, owing to the action of the lenticular lenslets. Figure 6.64 compares the horizontal and vertical gain of the two composite screens of Figure 6.63, which both have the lenticules oriented vertically. The widening of the viewing zone in the horizontal direction is evident. The other four screens of Figure 6.63, which do not use lenticular lenslets, have circularly symmetric gain curves.

Reflectance is a useful parameter for the characterization of rear projection screens. A front projection screen is designed to reflect, and the gain curve illustrates how well and in what form the screen does this. For rear projection screens, however, the gain curve shows how well the screen transmits and tailors the light distribution. It is still necessary to determine what portion of the ambient illumination will be reflected into the viewing volume. Reflectance curves are useful in determining this. Projection screens have two reflectance terms: diffuse reflectance and specular reflectance. Specular reflectance is mirror reflectance, where little scattering occurs and the angle of reflection is equal to the

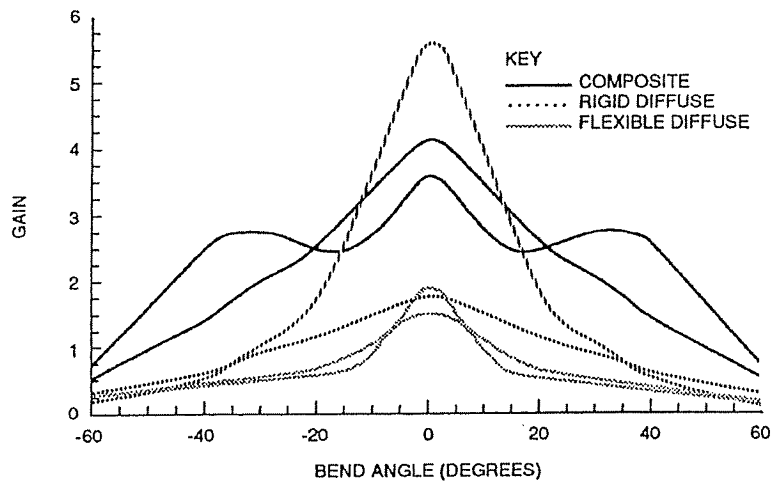

Figure 6.63 Gain vs. bend angle for six rear projection screens.

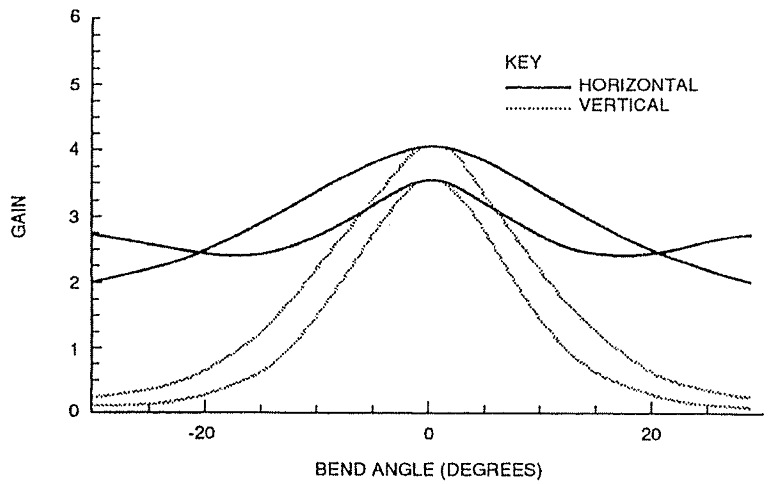

Figure 6.64 Horizontal and vertical gain for two rear projection screens with lenticular lenslets running vertically, widening horizontal viewing zone.

angle of incidence. Diffuse reflectance is scattered reflection, which occurs within a large range of angles. Diffuse reflectance causes a general image washout (low contrast), whereas specular reflectance may not be noticeable at most angles but can render the image unviewable at the particular specular angle.

Figure 6.65 shows reflectance versus angle for the six rear projection screens of Figure 6.63. Both specular and diffuse reflection is evident. The illumination was incident from the $+60°$ angle, leading to the greatest amount of reflection (the specular reflection) occurring at $-60°$. The specular reflection falls off rather quickly, and the amount of diffuse reflection can be read from the positive angle readings. The composite screen that does not exhibit strong specular reflection contains black reflection-inhibiting stripes within its structure for just this purpose.

Direct measure of image contrast provides information on how the gain and reflectance characteristics of the screen combine to present an image on the screen. Figure 6.66 shows image contrast versus bend angle for four rear projection screens under room ambient illumination (30–60 fc) conditions. All of the screens shown provide contrast sufficient for comfortable viewing over a wide range of angles. Figures 6.67 and 6.68 illustrate what happens to the image contrast as the ambient illumination incident on these screens is increased to 1000 fL and then to 2500 fL. The effect of both specular and diffuse reflection can be

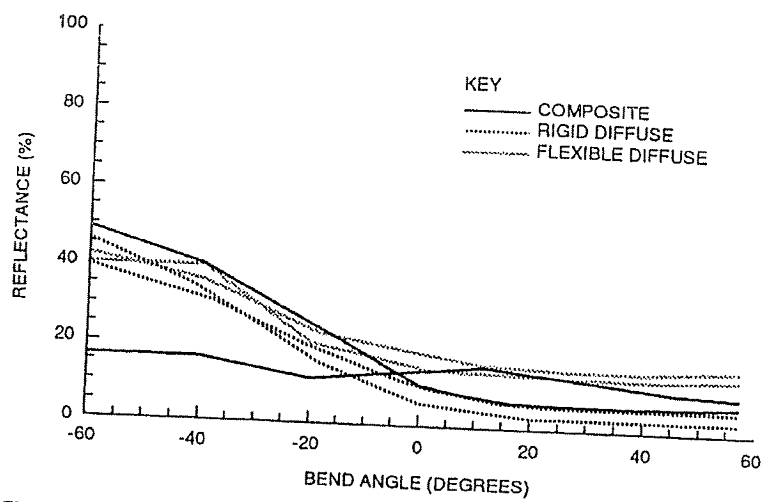

Figure 6.65 Reflection vs. bend angle for six rear projection screens from Figure 6.63.

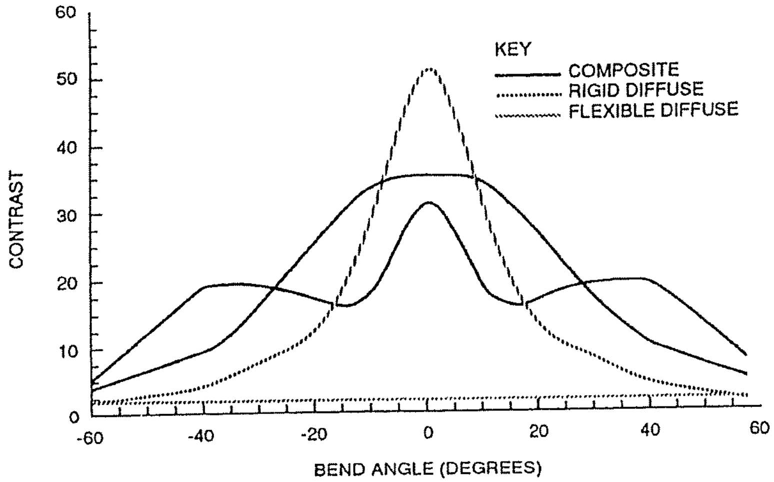

Figure 6.66 Contrast vs. bend angle in room ambient illumination for four rear projection screens.

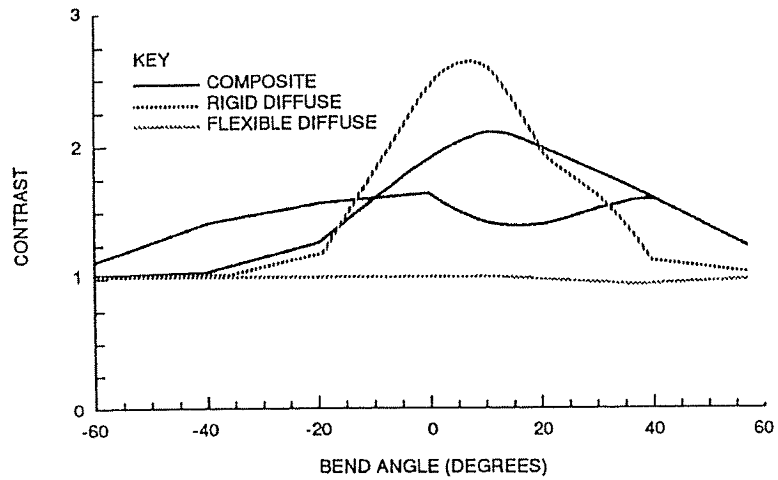

Figure 6.67 Contrast vs. bend angle in 1000-fc ambient illumination for the four screens from Figure 6.66.

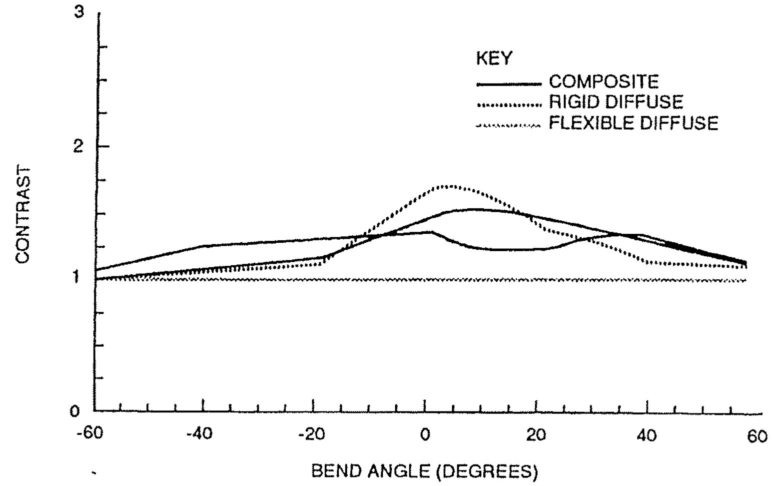

Figure 6.68 Contrast vs. bend angle in 2500-fc ambient illumination for the four screens from Figure 6.66.

seen. The ambient illumination, incident from +60°, lowers contrast the most where specular reflection occurs.

In addition to image contrast, the projection screen also can affect the colorimetry and resolution of the image, as well as introduce other artifacts that may be disturbing. The color balance of off-axis projection systems may not be even across the screen because of the differing incidence angles. Some lenticular lenslets are designed to correct for this effect. The lenticular lenslets can degrade the image resolution if they are not designed and implemented properly. The lenslet should be several times the size of the image pixel, or disturbing moiré effects occur. This depends on the exact lenslet design, however, and the absolute pixel size changes with changes in screen size, so each case must be evaluated separately. Whether effects such as these are significant depends on the specific application and implementation of the projection system. Recent works (Jenkins, 1981; Bradley et al., 1985) have characterized some of these phenomena.

6.6.4 Projection Screen Summary

Projection screen choices have expanded greatly in recent years, and choosing a screen for a particular application should take into account the specific image characteristics desired. Screen gain is the most useful screen parameter, describing the image luminance versus bend angle achieved from a particular screen.

High-gain screens have higher luminance at particular angles, but the luminance tends to fall off rather sharply, giving a smaller viewing angle. Low-gain screens supply lower image luminance, but the luminance remains constant over a larger range of angles, providing a larger viewing volume. Screen optical systems such as Fresnel lenses and lenticular lenslets have improved the light-tailoring ability of projection screens, providing even image luminance and a tailored, nonsymmetric gain curve. Ambient illumination degrades image contrast very rapidly. In high ambient illumination environments, rear projection screens with absorbing black stripes are helpful in maintaining image contrast.

6.7 CONVERGENCE AND IMAGE BLENDING

In most full-color projection displays the final image on the screen is generated by projecting and superimposing the images from separate monochrome image sources. Converging the display is the process of aligning the monochrome images on the screen so they overlap to create a full-color image. The individual images must be corrected for nonlinearities and geometric distortions and be focused across the screen. These functions are all included in the convergence process.

Mismatch between projected images is also a problem when the images from more than one projection display are tiled (i.e., mosaicked) to create a single picture. Image blending is the matching of two or more tiled projected images so edge seams and/or nonuniformities are not visible to the eye. The separate projected images must be aligned with each other for linearity and overlap at the edges, and their focus, luminance, and colorimetry must be matched.

6.7.1 Convergence

Converging a color projection display is necessary not only to align the monochrome images, but also to account and correct for the effects of individual optics and the unique nonlinearities associated with each image source. It has been shown (Mitsuhashi, 1990) that the individual red, green, and blue images must be converged to within ½ pixel to prevent compromising the display resolution. Techniques for converging projection displays include provisions for correcting linearity and focus errors in the image. These controls must be dynamic and adjust for drifting of the focus and geometry of the images over time.

The convergence techniques discussed in this chapter were developed primarily for CRT projection displays but can be applied to all types of projection displays, including laser and light valve displays. However, there are at least two types of display technology that do not need extensive converging, as their design inherently creates converged images. The GE single-light-valve Talaria display requires little convergence, as the colors are created and controlled by the same light valve. Fixed-matrix displays, such as AMLCLV projection displays,

are relatively easy to converge because their geometry is fixed. The geometry of the red, green, and blue images with respect to one another does not vary, so initial mechanical alignment of the images with respect to each other is usually all that is required over the life of the display.

Cathode-ray tube geometry and convergence errors are corrected by inputting a correction signal to the deflection current. This can be done by adding a signal to the main deflection yoke or, more commonly, by adding a separate coil to the deflection yoke to accept convergence signals (Fig. 6.69). The correction signal is a polynomial that is a function of the x and y deflection signals. The image is corrected by adjusting the coefficients of the polynomial terms. Each of the terms in the polynomial controls a different type of correction, as shown in Figure 6.70.

Focus across the screen is adjusted in much the same way, by adding a current and/or voltage signal to the focus circuit. When magnetic focusing is used, a separate focus coil is used to provide dynamic focus correction.

Correction signals historically have been adjusted by analog means, using a potentiometer for each of the polynomial terms. Analog circuits drift, however, which means that the display must be reconverged after a period of use. This has led to the development of convergence and focus correction circuitry that is either completely or partly digital to minimize drift, improve accuracy, and lower the difficulty of converging (Holmes, 1987a). Correction values corresponding to the different parts of the image are stored in memory and read out as needed (Fig.

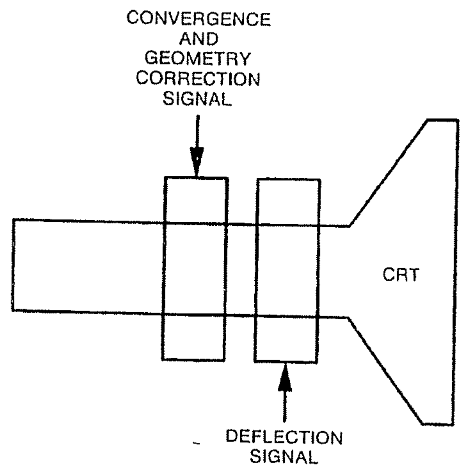

Figure 6.69 Separate deflection yoke on CRT used to provide convergence corrections.

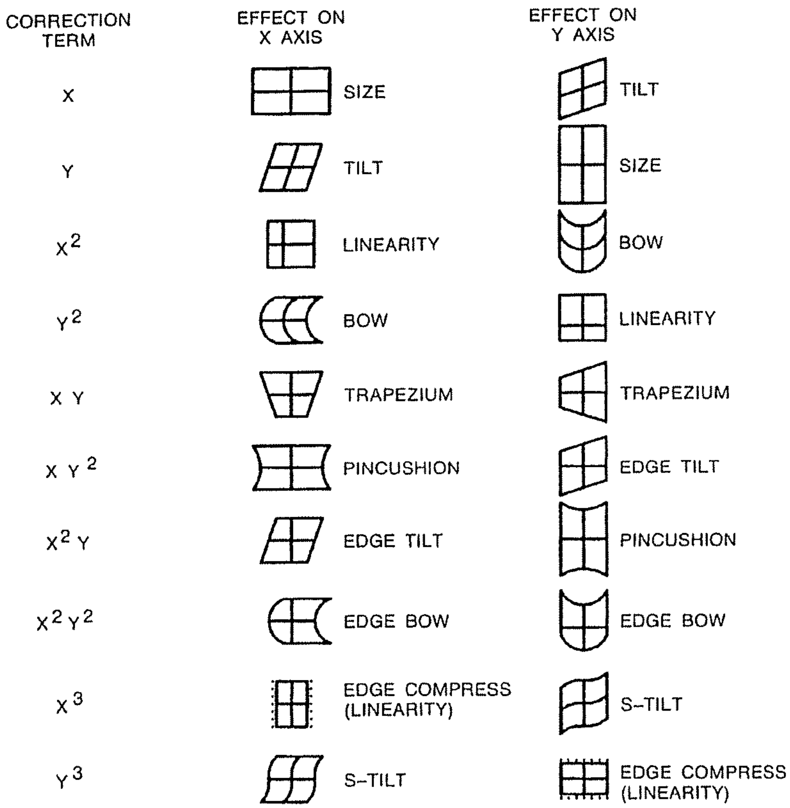

Figure 6.70 CRT convergence and geometry correction functions (Elmer, 1982).

6.71). Storing the correction function in digital memory eliminates that portion of drift caused by the potentiometers.

Each monochrome image source will have at least one correction matrix for convergence errors (sometimes more than one is used) and a correction matrix for focus errors. Several methods have been developed that simultaneously minimize memory requirements and maximize correction accuracy and resolution (Holmes, 1987a; Lyon and Black, 1984). Correction values are stored for spe-

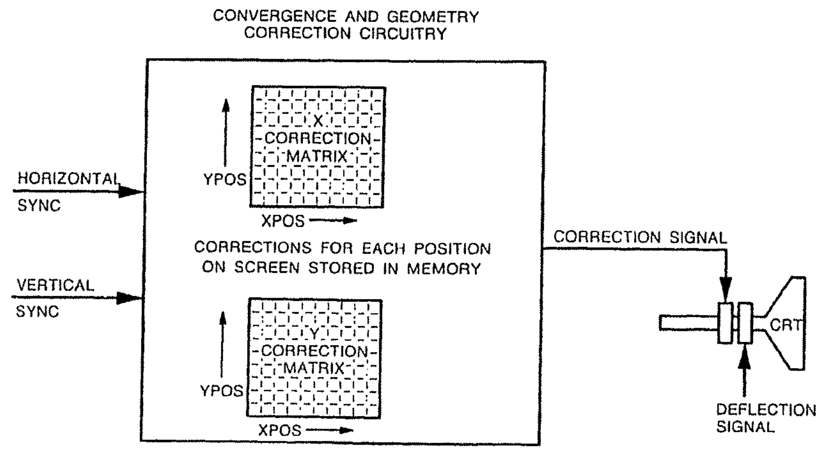

Figure 6.71 Correction matrices store correction values according to position on screen.

cific points, and interim values are interpolated, saving memory space while providing high-resolution correction.

Initial values for convergence and focus correction matrices are determined at the first display setup. A test pattern is projected, usually a grid pattern. An interactive program is used with which the operator enters correction values and immediately sees the effect on the image. The green image is corrected first for nonlinearities and geometric distortions. After the green image is geometrically correct, the red and blue images are projected, and correction values are entered until these images superimpose on the green image. These convergence correction values are stored in corresponding memory chips for each CRT.

Focus correction values are entered in the same manner. The individual images are projected, and focus correction values are manually entered for specific positions across the screen. Again, interpolation is used to fill in the interim points. These values are stored in the focus correction memory for each CRT.

Once the image is initially converged and focused, provisions must be implemented for periodic adjustments for drift over time and temperature. Some display systems permit periodic manual resetting of focus and convergence, thus correcting for changes over time. This can be time-consuming and does not permit continuous system use, so automatic convergence adjustments are becoming standard.

Automatic focus and convergence adjustment systems incorporate feedback from the image to provide data to reconverge and refocus the image. These systems are of many configurations, including optical sensors at the screen (Lyon and Black, 1984) or on a mirror for detecting errors. Some systems use data generated from the actual image to provide feedback, while others project special alignment images outside the field of view or during flyback. One system uses a CCD camera to look at the entire image and detect errors (Kanazawa and Mitsuhashi, 1989); this permits precise error detection and correction.

6.7.2 Image Blending

In applications where the required image luminance and/or resolution cannot be furnished by a single projector, multiple-projector systems can be used to create a single image. Large multisegment images can be assembled in a tiled configuration or an area-of-interest configuration. In either approach the separate projected images must be matched in linearity, geometry, color, and luminance, so the viewer sees a continuous seamless image.

In the tiled approach, the images from several projectors are lined up in a matrix, creating one large image that is a mosaic of smaller images (Fig. 6.72). The segments of the tiled image have similar resolution, creating one large image with constant resolution throughout. This technique is most useful where high resolution is needed in all parts of the display, such as in multiviewer large-screen entertainment systems, simulator displays, or command and control centers.

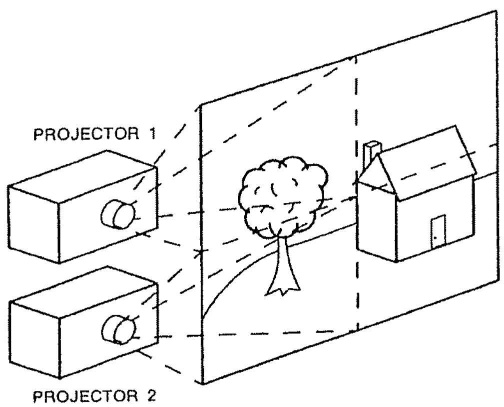

Figure 6.72 Tiled image approach to multiprojector scenes, using four projectors (projectors 3 and 4 hidden).

The area-of-interest approach was developed for single-viewer simulator applications (Cowdry, 1985; Spooner, 1982). Projection displays are used in flight simulators to present a wide field-of-view image to the pilot. The projected imagery fills the pilot's visual field of view, giving the sensation that the projected imagery is the outside world. It has been shown that the human eye sees high resolution only in the forward foveal view and not peripherally (Bunker and Fisher, 1984). The area-of-interest technique was developed to take advantage of this fact, providing high resolution only in the direction in which the viewer is looking. In this way display hardware and processing power are not wasted displaying resolution and detail that will not be used. In most cases two projectors are used, one to project a low-resolution background, the other to project a high-resolution inset. These two images can be optically combined and projected onto the screen with a single projection system as shown in Figure 6.73. The high-resolution inset, typically with a field of view of about 25°, tracks the viewer's eyes. The low-resolution background fills the remainder of the field of view.

The area-of-interest technique has the advantage of requiring less projection display hardware and image-processing power but can be used in single-viewer applications only, and adds the requirement of head-tracking the high-resolution inset.

Regardless of which multiple-image technique is used, the images must be aligned and blended at the edges for geometry, convergence, and luminance, and overall for color (in addition to convergence of each individual channel). Edge

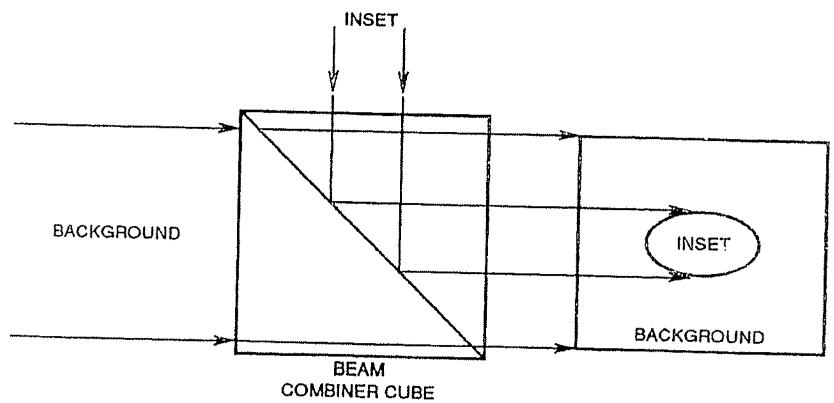

Figure 6.73 The background and inset in an area-of-interest multiple-projector image provide a high-resolution image where the viewer is looking, with a low-resolution background filling the field of view.

matching is particularly critical, because the eye is very sensitive to discontinuities. Attempts to butt edges together without blending are rarely successful, resulting in either a luminance line or a gap, as well as geometric mismatches (Figs. 6.74 and 6.75).

Image-blending techniques are similar to those used for convergence and fo-

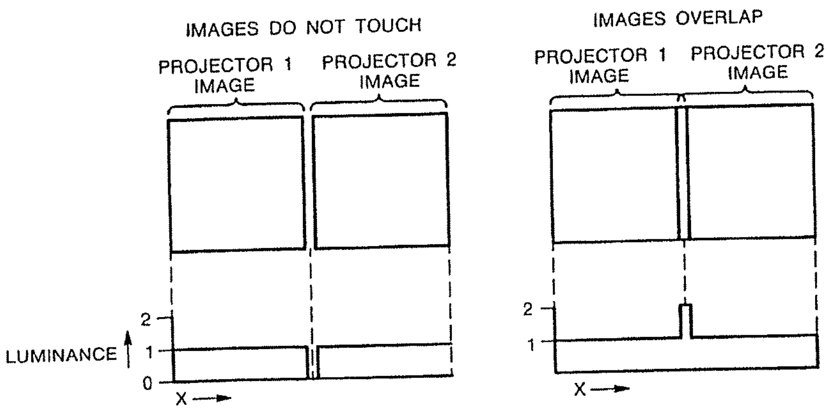

Figure 6.74 Luminance nonlinearities result when edges are not blended.

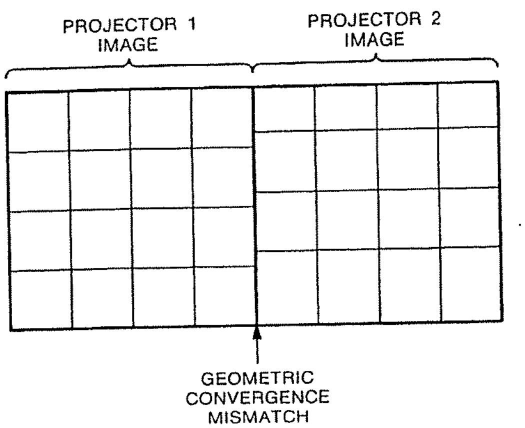

Figure 6.75 Line discontinuities result when edges are not blended.

cus correction, consisting of control circuitry for matching color, intensity, and linearity of separate projected images (Holmes, 1987b, 1989; Green and Lyon, 1988). The color hue of each individual projector is adjusted until all projected images are matched for white. This can be done by eye or with a spectrophotometer. Systems have been developed that perform these adjustments automatically by using sensors at the screen (Lyon and Black, 1984).

Linearity and geometry matches at the edges are accomplished by using the individual convergence circuitry of each projector. A grid pattern is again used, and interactive convergence circuitry is used to match the geometry of the edges until there are no linearity mismatches. Recent techniques have increased the accuracy and ease of use of this process. These techniques include adding a grid of lights to the screen to give the operator a pattern to converge to and using a finer grid at the edges to allow better edge linearity matching (Green and Lyon, 1988).

Intensity nonlinearities are eliminated by permitting the images to overlap and attenuating the luminance at the edges, resulting in a smooth transition. With a perfect blend the two image luminances meet at the 50% luminance points, resulting in even luminance across the screen (Figs. 6.76 and 6.77). If the edges do not match up exactly, the luminance variation caused by the slight mismatch would not create as large a discontinuity as if the image luminance were to fall off quickly.

In the tiled approach the edge luminance is gradually attenuated, using either a fixed attenuation function or an operator-adjustable attenuation. In the area-of-interest technique the background is fully attenuated where the inset is to be, with an edge gradient leading to no attenuation throughout most of the image. The

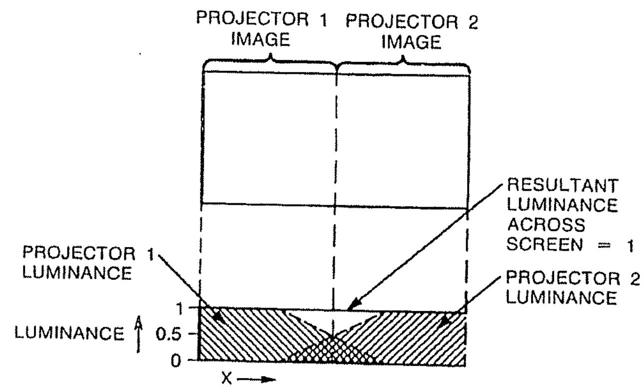

Figure 6.76 Luminance blending of tiled images.

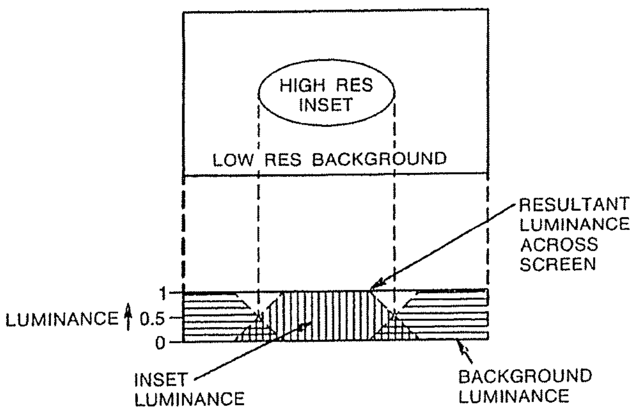

Figure 6.77 Luminance blending of area-of-interest images.

inset is attenuated at its outer edges. The attenuation of the inset and background is adjusted until a smooth transition occurs between the two.

Automatic feedback systems are used in the image-blending process to correct for errors over time, just as with the convergence process. Sensors are used to detect discontinuities in linearity, convergence, color, or luminance and make the proper corrections.

6.7.3 Convergence and Image Blending: Summary

Convergence is the process of correcting projected image geometry and focus errors and aligning the monochrome images with each other. This can be a difficult and time-consuming process. If multiple projectors are used to create a single image, as in the tiled or area-of-interest techniques, the process is expanded to include matching the luminance, geometry, and chromaticity of the separate images. Convergence and image-blending circuitry has evolved from analog to digital systems where correction values are stored in memory according to their location on the image. Techniques for automatic error detection and correction provide stable convergence and blending once the system is initially set.

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